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Strength Capabilities and Load Requirements While Performing Torquing Tasks in Zero Gravity

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ACKNOWLEDGEMENTS

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INTRODUCTION

Background

Knowledge of astronaut strength capabilities is of interest within many areas of NASA research. Astronauts are called upon to perform a variety of tasks while in orbit. Their ability to perform a task is partly determined by their strength for that particular task. Thus, an important step in task planning, development, and evaluation is to determine the ability of the humans performing it.

Many tasks require the use of tools. There is a wide variety of tools in use on the Shuttle and planned for Space Station for purposes of maintenance, experiment setup, satellite repair, etc. A majority of these tools are used to apply a torque to tighten and/or loosen fasteners of some type.

While performing maintenance and other tasks, astronauts typically use foot restraints to remain in position at the worksite and to provide stabilization for their bodies. In addition, they may grasp onto handrails with the hand not using the tool. For design purposes, it is useful to know what loads are transmitted to these structures while the tool is being used.

Many factors affect how much output an astronaut can produce with a tool: the type of tool used and the characteristics of that tool; the position and orientation of the fitting on which the tool is being used; the type, location and orientation of foot restraints and handrails. It is of interest to determine the effect of each of these characteristics. This study looked at the characteristics of the position and orientation of the fitting on which the tool was being used.

Purposes

This study was a generic examination of the loads produced by individuals performing maximal efforts with a torquing tool. Specifically, the purposes were to:

1. Determine how much strength individuals have when performing torquing tasks

2. Quantify the loads placed on foot restraints while performing torquing tasks

3. Examine the effects of orientation and direction of rotation of the tool on strength effectiveness

METHODS

Subjects

Eight males volunteered to be subjects in this experiment. All subjects had passed an Air Force Class III Flying physical, and signed an informed consent to be in the study acknowledging their understanding of the procedures and risks. A summary of the subjects' heights and weights is given in the table below:

Table 1. Summary of Subject Information

	Mean	St. Dev.
Height (cm)	176.4	3.8
Weight (kg)	77.3	8.3

These values compare to the male astronaut database (Rajulu and Klute, 1993) in which the average height was 178.5 cm (±6.2), and the average weight was 76.0 kg (±8.1).

Apparatus

KC-135 Aircraft

Tests were conducted aboard NASA's KC-135 aircraft. The KC-135 is a modified jet that is capable of flying parabolic arcs with a vertical acceleration equal to the acceleration due to gravity. Thus, during the parabola, passengers and equipment within the plane experience virtual zero gravity. Each parabola lasts approximately 25 seconds, with a typical flight consisting of 40 parabolas. This experiment was conducted over two flights on consecutive days.

Equipment Setup

A general purpose test stand was equipped for this study (figure 1). The stand was approximately 183 cm (72 in.) tall, 91 cm (36 in.) wide, and 137 cm (54 in.) long, in an "L" shape. A tri-axial force platform (Kistler model 9281B12) was positioned at the work location on the stand. At the center of the forceplate was a custom built multi-node torque application fixture (TAF) with five 1.11 cm (7/16 in.) hex fittings oriented along three orthogonal axes as shown in figure 2. To the left of the force platform was an EVA handrail, located 36 cm (14.2 in.) from the TAF.

A second force platform was mounted on the base of the test stand. An adjustable foot restraint system was attached to this force platform. The pitch angle of the foot restraint was set at 20°.

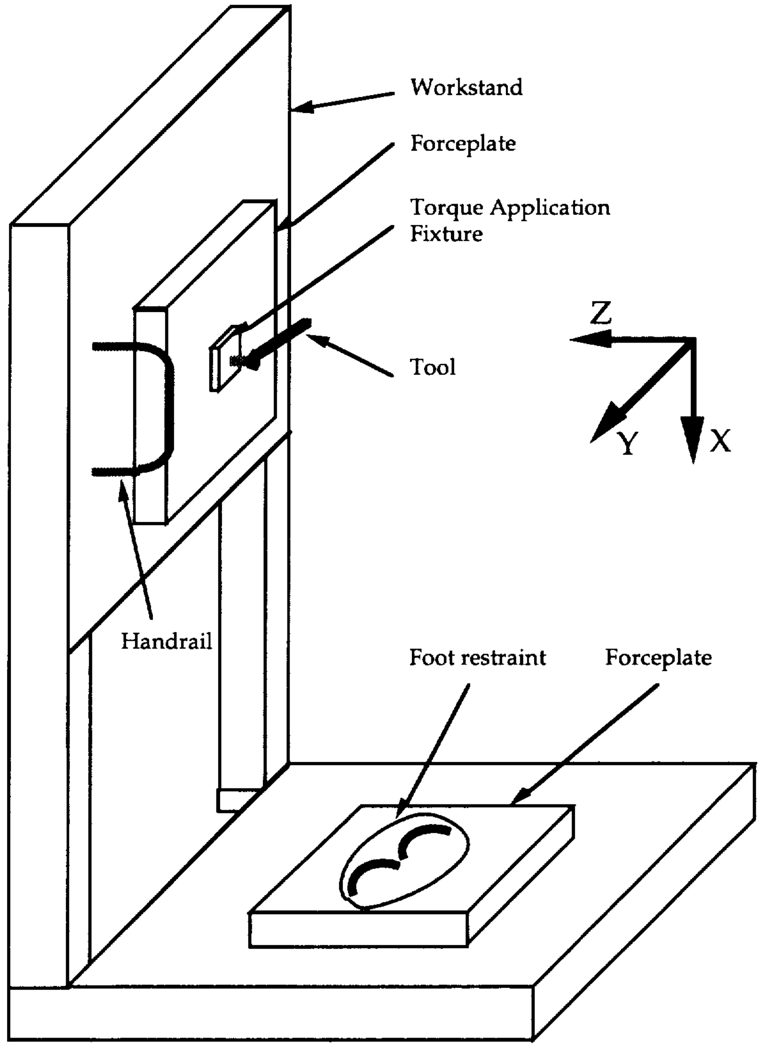

Figure 1. Test apparatus setup.

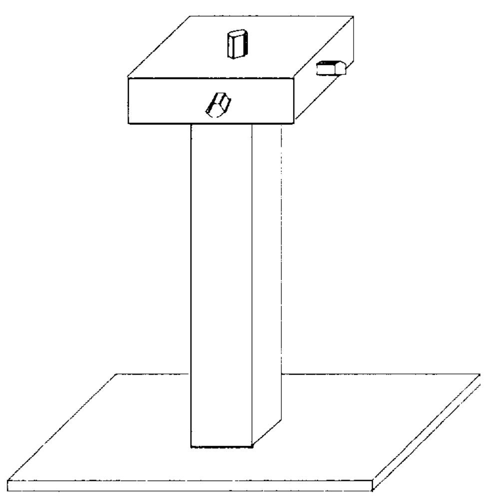

Figure 2. Drawing of the Torque Application Fixture (TAF).

A commercially available torquing device (Craftsman 1/2" socket wrench) was used as the tool in this study. It was approximately 25 cm (10 in.) in length and 1.7 cm (0.66 in.) in diameter at the handle. A 1.11 cm (7/16 in.) socket was used. The distance from the center of the socket to the center of the handle, where the tool was gripped, was 18 cm (7 in.).

The test stand was mounted on the KC-135 aircraft, using six 0.95 cm (3/8 in.) bolts. A data acquisition system (Ariel Performance Analysis System) was mounted near the stand. Two video cameras were positioned nearby to record the study qualitatively.

A global coordinate system was defined (figure 1) in which the X-axis was parallel to the longitudinal axis of the subject's body (head to foot), the Y-axis corresponded to the mediolateral axis of his body (right to left), and the Z-axis was perpendicular to the coronal plane of his body (back to front).

Experimental Design

This study implemented a randomized block design using the conditions of tool orientation (TO) and direction of effort (DE). With the TAF, there were many possible orientations for the tool, of which six were used (table 2). Three of the five TAF fittings were used, those in the +X, -Y, and -Z directions. For each of these fitting alignments, the tool was aligned in two different directions. For the +X fitting, the tool was aligned with the -Y and -Z axes; for the -Y fitting, the tool was aligned with the +X and -Z axes; and for the -Z fitting, the tool was aligned with the +X and -Y axes. Thus, there were a total of six conditions for TO. The DE condition could either be positive or negative. This refers to whether the effort was along one of the positive or negative axes (which axis depended on the TO). Table 2 lists the direction of effort for each of the TO conditions in terms of both the coordinate axes and the direction relative to the subject's perspective.

Table 2. List of Values for the Tool Orientation Conditions

TOOL ORIENTATION			
Condition ID	Fitting Alignment	Tool Alignment	Directions of Effort
XY	+X	Y	±Z - away/towards
XZ	+X	Z	±Y - left/right
YX	-Y	X	±Z - away/towards
YZ	-Y	Z	±X - down/up
ZX	-Z	X	±Y - left/right
ZY	-Z	Y	±X - down/up

With six values for TO and two for DE, there were a total of 12 conditions to test. Each condition was performed by the subjects three times, for a total of 36 trials. The subjects performed four trials per parabola on the KC-135. Conditions were randomized and balanced within each subject's nine parabolas.

Procedures

Before the onset of zero gravity, the subject was reminded of the four trials he would perform. The subject stood with his feet in the foot restraints. His left hand grasped onto the handrail. With his right hand, he positioned the tool on the designated fitting and in the first orientation for that parabola. He produced a maximal effort on the tool in the first specified direction. Then he switched the ratchet mechanism on the socket wrench and produced a maximal effort in the opposite direction. Next, he rotated the tool to the second orientation and produced two more maximal efforts in opposite directions.

Data Collection

There were two forceplates used in this study. One had the TAF mounted on it and was attached to the test stand at the work location. The other was also mounted to the test stand and was under the foot restraint. Load cell data from the forceplates were collected at a rate of 250 Hz with the data acquisition system and stored on the computer hard disk. Later, files were converted to a format compatible with other software.

Data Analysis

Software was written to analyze the data. Initial processing put the data into the form of time-based X, Y and Z components of the resultant force at the tool site and at the foot restraints for the duration of the zero-gravity interval (approximately 25 sec). For each parabola, the window of data corresponding to the actual performance of each of the four trials was determined. Within each window, the peak magnitude for each of the six force components was obtained and corrected for baseline offset. The data was transformed from local coordinate systems based in the forceplates to the global coordinate system shown in figure 1.

Recall that each combination of conditions was repeated by each subject three times. For analysis purposes, the three repetitions were treated and are reported in two ways. First, the maximum of the three repetitions was taken as representative for each subject (MAX). Justification for this was based on the fact that the study was intended to examine maximal efforts; thus, anything less than their peak effort should not be considered. A second technique involved taking the average of the three repetitions as representative of each subject (AVG). These values are more useful and statistically relevant when looking at typical loads that occur when an individual performed a maximal effort (as opposed to the maximal effort itself).

An analysis of variance (ANOVA) was performed on the data to detect differences within the conditions. A significance level of 0.05 was chosen to determine whether or not detected differences were significant.

RESULTS

Numerical Data

The raw results from this study appear in the tables below. Tables 3 through 5 present the data from the forceplate at the work site in the X, Y and Z directions, respectively. Each row of the tables corresponds to a single combination of test conditions (tool orientation and direction of effort). The first two columns of numbers are the mean and standard deviation of the eight subjects' values for the maximum of their repeated trials (MAX). The last two columns of numbers are the mean and standard deviation of the average of each subject's efforts (AVG). All values are in Newtons (N). Recall that 1 N is equivalent to 0.225 lb.

Table 3. Forces (N) on TAF in the X Direction Averaged Across Subjects

Test Conditions		Maximum		Average	
TO	DE	Mean	St Dev	Mean	St Dev
XY	away	-370.8	172.4	-322.8	144.4
XY	towards	3.9	144.2	6.5	86.7
XZ	left	-176.2	87.1	-133.3	93.7
XZ	right	-85.6	83.2	-47.0	58.9
YX	away	-223.5	141.5	-140.3	77.2
YX	towards	-158.6	70.6	-98.3	69.5
YZ	down	549.3	117.2	485.4	113.6
YZ	up	-749.6	198.6	-698.5	170.9
ZX	left	-46.7	154.2	-34.0	85.2
ZX	right	-48.6	129.4	-37.9	87.5
ZY	down	525.5	138.8	481.2	118.9
ZY	up	-693.6	215.2	-642.8	219.5

Table 4. Forces (N) on TAF in the Y Direction Averaged Across Subjects

Test Conditions		Maximum		Average	
TO	DE	Mean	St Dev	Mean	St Dev
XY	away	57.7	105.9	38.5	74.6
XY	towards	213.2	72.7	152.1	48.9
XZ	left	388.5	72.5	347.7	72.5
XZ	right	-450.8	127.6	-403.5	93.0
YX	away	64.9	108.5	51.0	56.0
YX	towards	140.9	96.2	113.4	102.9
YZ	down	120.8	97.0	92.4	86.9
YZ	up	82.8	89.6	79.8	63.4
ZX	left	457.5	94.3	420.4	98.0
ZX	right	-549.6	151.3	-513.0	151.9
ZY	down	99.4	81.3	86.4	62.4
ZY	up	71.9	144.1	67.3	99.4

Table 5. Forces (N) on TAF in the Z Direction Averaged Across Subjects

Test Conditions		Maximum		Average	
TO	DE	Mean	St Dev	Mean	St Dev
XY	away	390.5	101.8	351.6	86.8
XY	towards	-497.8	130.2	-417.0	109.8
XZ	left	164.3	112.9	115.7	104.2
XZ	right	-134.1	35.0	-96.0	49.4
YX	away	436.5	110.6	369.1	77.7
YX	towards	-492.6	139.3	-413.6	116.8
YZ	down	21.1	156.5	-16.3	55.6
YZ	up	233.4	89.1	212.6	88.0
ZX	left	157.4	94.9	114.9	58.8
ZX	right	-185.8	65.4	-152.2	59.7
ZY	down	-154.1	48.8	-124.9	60.1
ZY	up	191.5	95.4	156.6	75.3

Tables 6 through 8 present the data from the foot restraint forceplate in the X, Y and Z directions, respectively. Each row of the tables corresponds to a single combination of test conditions (tool orientation and direction of effort). The first two columns of numbers are the mean and standard deviation of the eight subjects' values for the maximum of their repeated trials. The last two columns of numbers are the mean and standard deviation of the average of each subject's three efforts. All values are in Newtons (N).

Table 6. Forces (N) on Foot Restraint in the X Direction Averaged Across Subjects

Test Conditions		Maximum		Average	
TO	DE	Mean	St Dev	Mean	St Dev
XY	away	495.0	210.5	416.4	174.7
XY	towards	274.0	115.4	207.3	74.8
XZ	left	272.1	200.7	233.7	170.5
XZ	right	154.5	118.3	83.9	88.3
YX	away	280.2	219.8	182.2	135.8
YX	towards	336.3	129.8	266.1	101.8
YZ	down	-563.9	184.1	-458.2	211.5
YZ	up	947.3	239.1	890.5	220.1
ZX	left	50.4	256.0	41.4	164.8
ZX	right	108.4	163.6	87.4	96.0
ZY	down	-530.9	240.7	-482.8	206.4
ZY	up	856.9	255.3	802.1	265.5

Table 7. Forces (N) on Foot Restraint in the -Y Direction Averaged Across Subjects

Test Conditions		Maximum		Average	
TO	DE	Mean	St Dev	Mean	St Dev
XY	away	50.4	62.6	40.7	42.5
XY	towards	-77.8	20.4	-63.3	22.8
XZ	left	-80.8	29.7	-57.0	29.5
XZ	right	64.2	50.9	53.2	41.4
YX	away	14.2	58.4	1.9	28.3
YX	towards	-76.3	21.5	-59.0	18.0
YZ	down	-43.0	45.2	-34.8	25.3
YZ	up	32.9	41.2	13.5	33.4
ZX	left	-96.2	45.8	-76.0	35.0
ZX	right	87.7	34.7	76.5	32.0
ZY	down	-87.8	20.6	-72.6	23.3
ZY	up	48.0	46.1	40.5	24.9

Table 8. Forces (N) on Foot Restraint in the Z Direction Averaged Across Subjects

Test Conditions		Maximum		Average	
TO	DE	Mean	St Dev	Mean	St Dev
XY	away	-189.8	82.1	-169.5	67.7
XY	towards	13.2	98.2	-4.3	61.5
XZ	left	-21.6	94.6	-13.1	69.5
XZ	right	-53.5	53.3	-38.8	40.8
YX	away	-165.1	88.4	-120.0	50.2
YX	towards	2.8	100.4	-6.2	56.2
YZ	down	128.9	42.3	111.6	32.7
YZ	up	-202.3	74.6	-186.9	68.4
ZX	left	9.7	103.1	4.1	82.3
ZX	right	-10.1	68.4	-13.4	42.9
ZY	down	161.0	62.6	148.6	52.8
ZY	up	-220.8	81.9	-188.5	73.3

Graphical Presentation

Figures 3 through 14 present the data from the above tables in the form of bar charts. Each figure shows the data from one test condition (tool orientation and direction of effort). The test condition is indicated by the diagram which accompanies each graph. The diagram depicts the forceplate and TAF fittings, labeled X, Y and Z. The tool direction is shown and the direction of force application is indicated by the arrow. Error bars indicate ±1 standard deviation from the mean. Note that the scales on the force axis are not the same on all graphs.

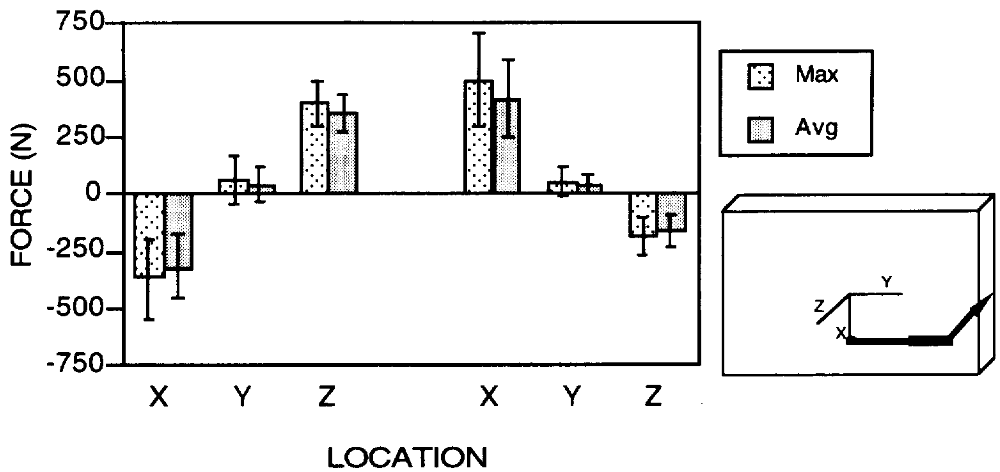

Figure 3. Bar chart of forces resulting from an effort away from the subject (+Z) with a TO of "XY."

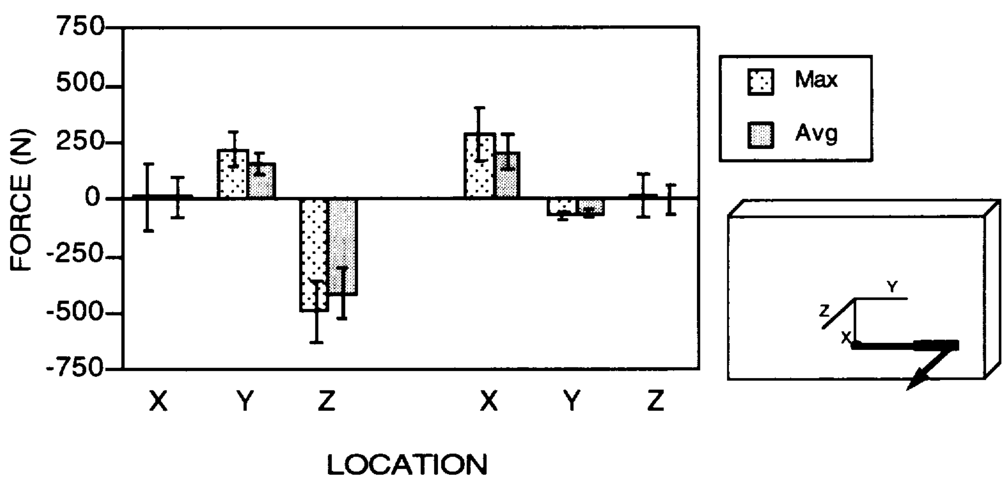

Figure 4. Bar chart of forces resulting from an effort towards the subject's body (-Z) with a TO of "XY."

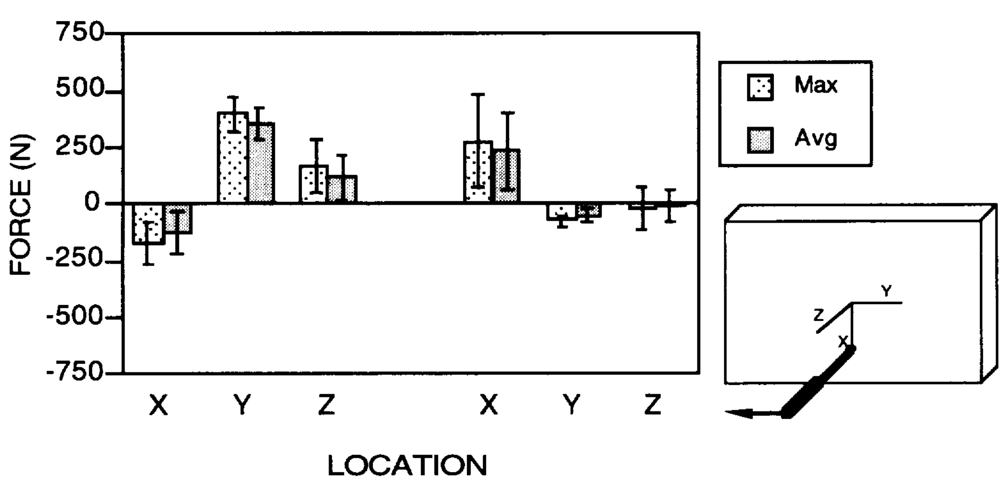

Figure 5. Bar chart of forces resulting from an effort to the left of the subject (+Y) with a TO of "XZ."

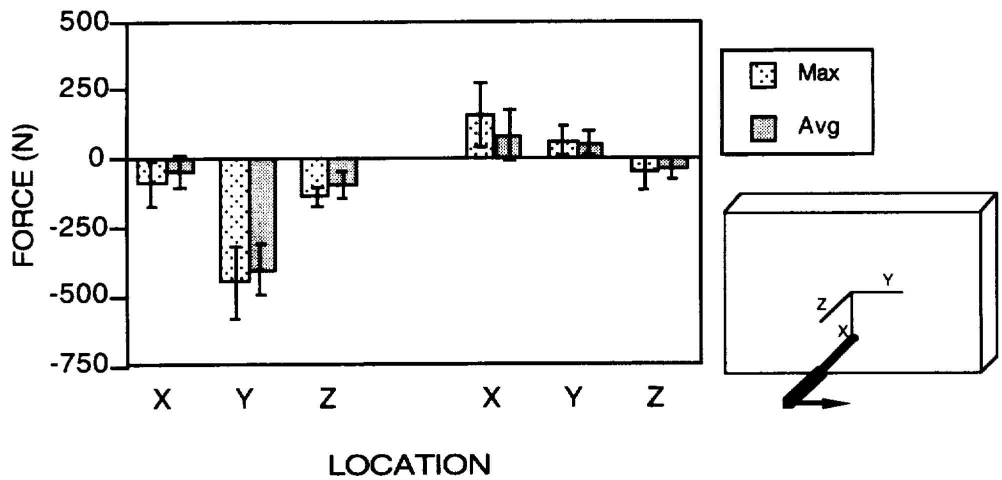

Figure 6. Bar chart of forces resulting from an effort to the right of the subject (-Y) with a TO of "XZ."

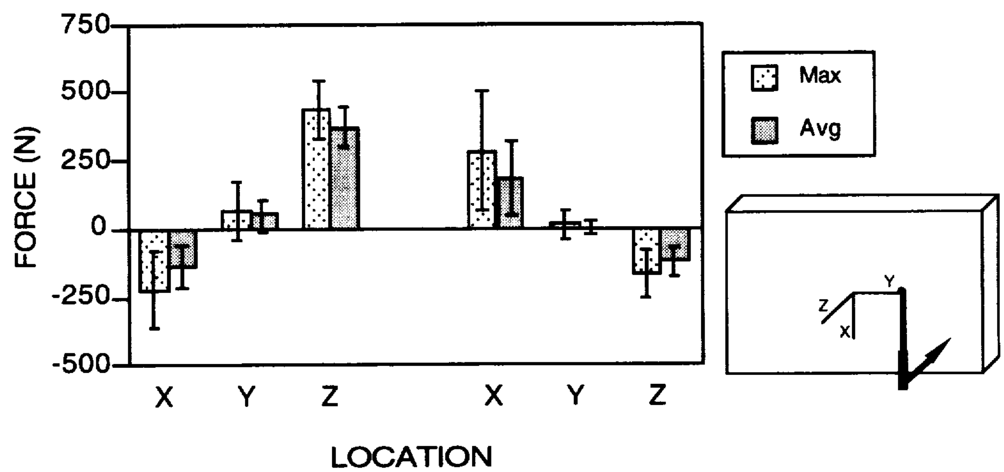

Figure 7. Bar chart of forces resulting from an effort away from the subject (+Z) with a TO of "YX."

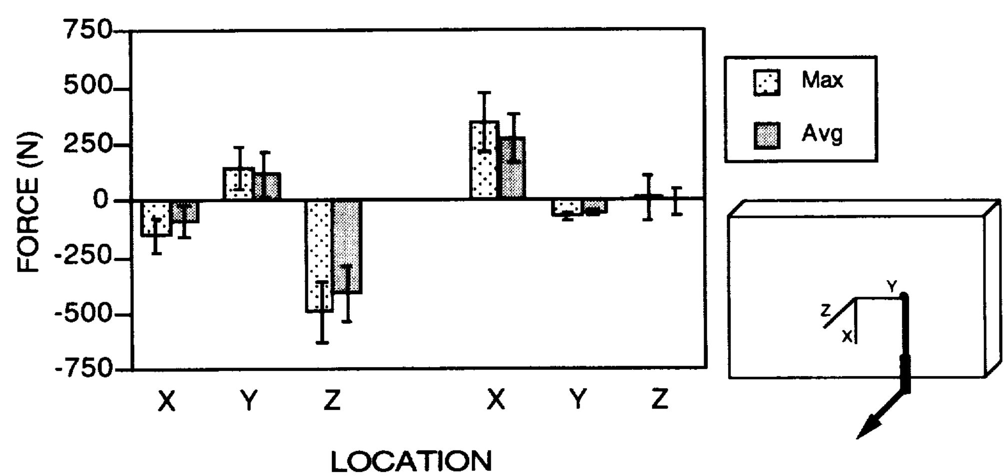

Figure 8. Bar chart of forces resulting from an effort towards the subject (-Z) with a TO of "YX."

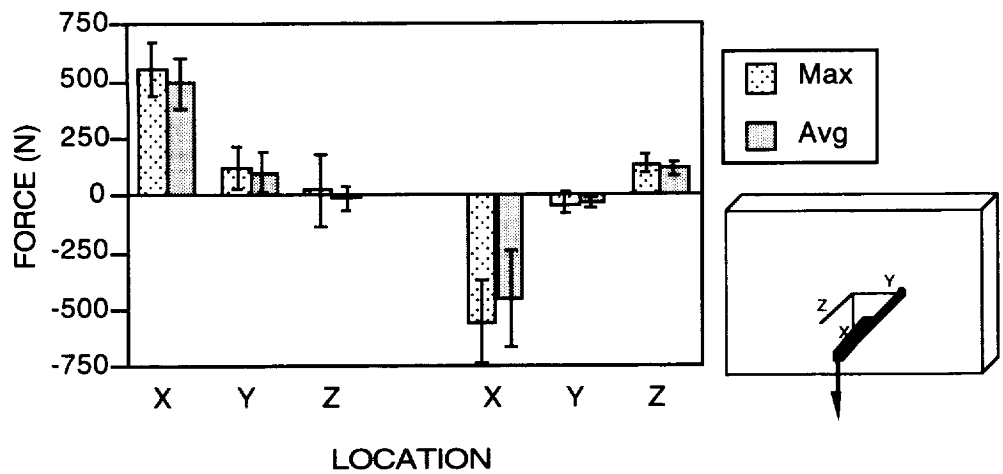

Figure 9. Bar chart of forces resulting from an effort towards the subject's feet (+X) with a TO of "YZ."

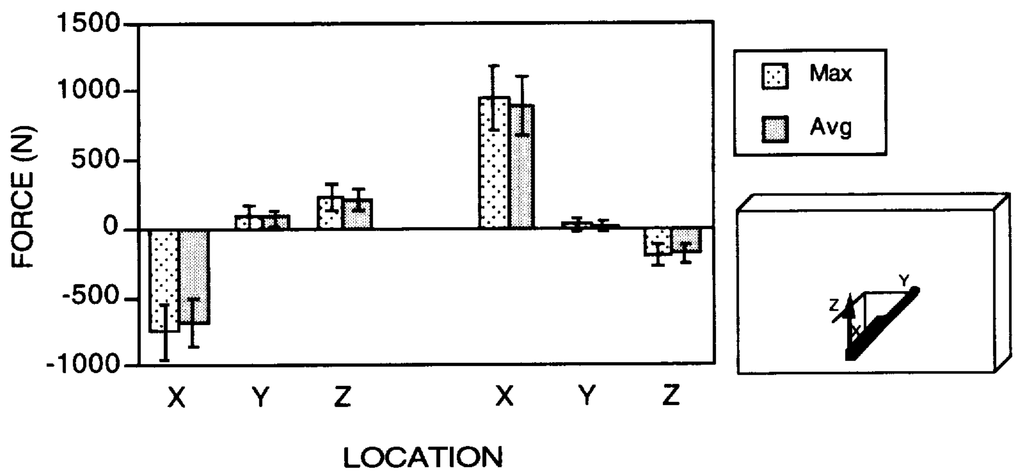

Figure 10. Bar chart of forces resulting from an effort up towards the subject's head (-X) with a TO of "YZ."

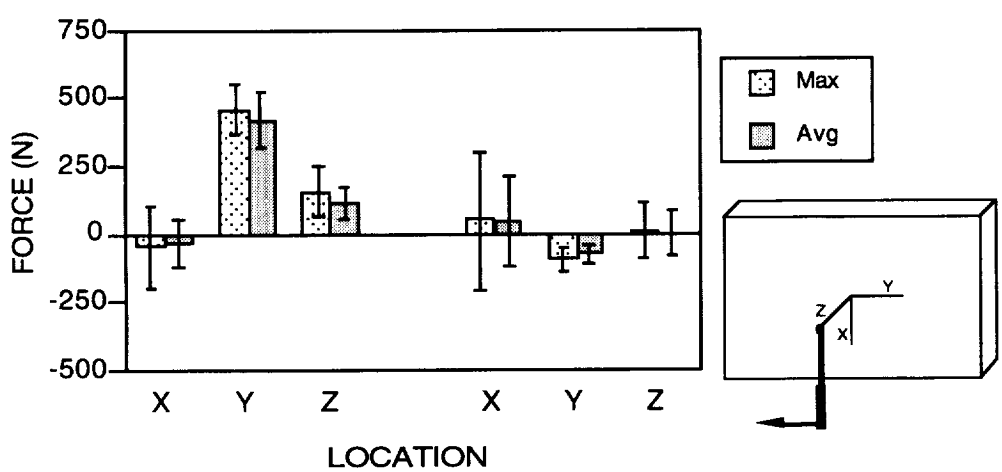

Figure 11. Bar chart of forces resulting from an effort to the left of the subject (+Y) with a TO of "ZX."

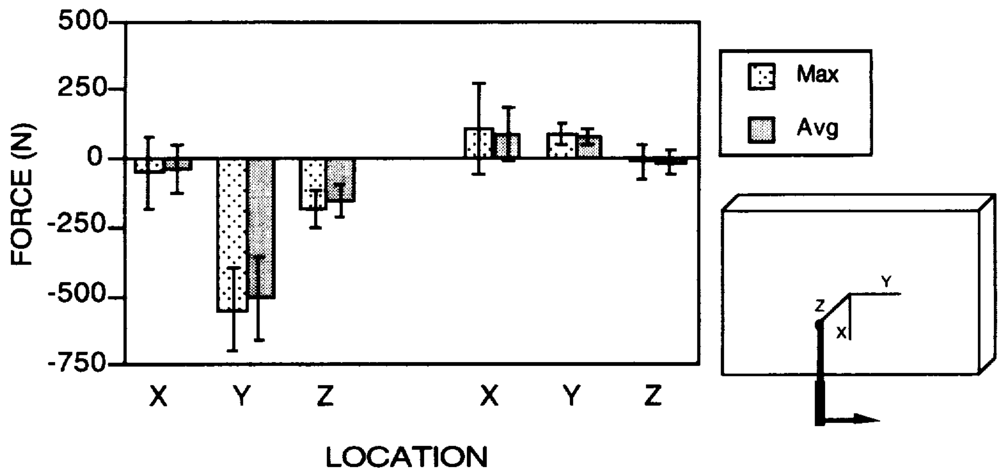

Figure 12. Bar chart of forces resulting from an effort to the right of the subject (-Y) with a TO of "ZX."

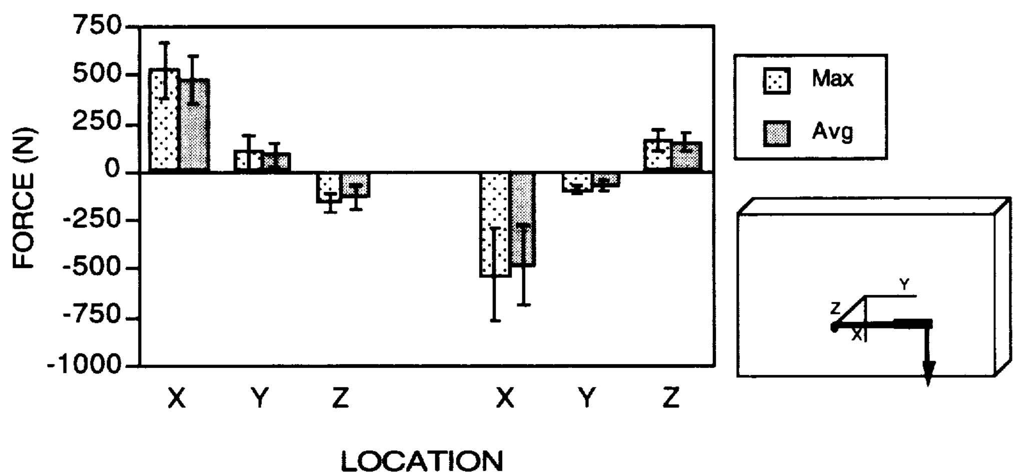

Figure 13. Bar chart of forces resulting from an effort towards the subject's feet (+X) with a TO of "ZY."

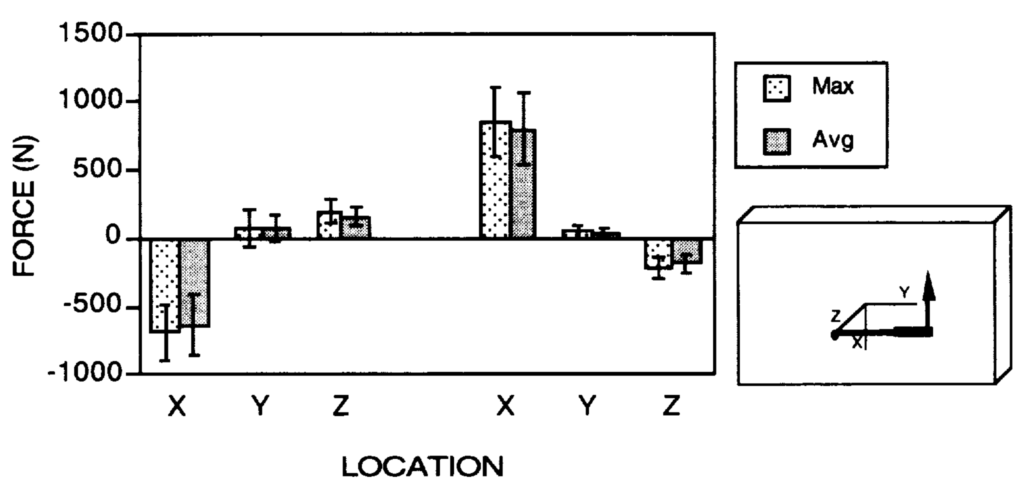

Figure 14. Bar chart of forces resulting from an effort up towards the subject's head (-X) with a TO of "ZY."

Force Effectiveness

An important component of the data presented in the above tables and graphs is the actual effectiveness in generating a force in the desired direction. Table 9 presents the force that resulted in the direction of applied effort for each of the test conditions, averaged across subjects. For each of the six coordinate directions, there were two possible tool orientations which were averaged. There were no statistical differences between any of the two TOs. Data taken from MAX and AVG are both presented. All values are in Newtons (N).

Table 9. Forces in Direction of Effort

Direction of Applied Force	Tool Orientations	MAX	AVG
DOWN	YZ and ZY	537.4	483.3
UP	YZ and ZY	721.6	670.6
LEFT	XZ and ZX	423.0	384.0
RIGHT	XZ and ZX	500.2	458.3
AWAY	XY and YX	413.5	360.3
TOWARDS	XY and YX	495.2	415.4

These data are repeated graphically in the chart below. Error bars representing ±1 standard deviation are included.

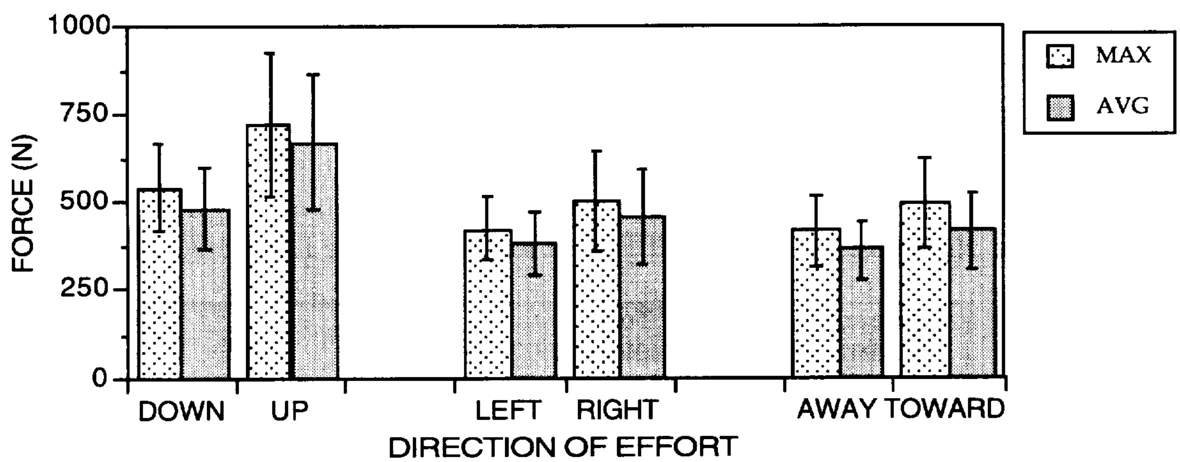

Figure 15. Bar chart of forces in the applied direction for each of the test conditions.

Statistical analysis revealed that there was a significant difference between the "up" effort and all the others with both MAX and AVG variables. The "up" effort resulted in a greater amount of force production.

Statistical analysis on the forces in the applied direction revealed that the effort in an upward direction was significantly different from that in the other five directions. This was not surprising, since with this condition, the operator could push up with his feet and legs. No differences were seen among the other five directions of effort.

When the data were grouped and analyzed by the Fitting Orientation (FO), it was seen that with the FO along the X axis, the applied force was significantly different from both the Y and Z conditions (MAX: X 432, Y 557, Z 556; AVG: X 380, Y 492, Z 514). This difference can be attributed to the fact that, with the FO along the X axis, the operator could not apply an effort in the upward direction as he was able to with the FO in the Y and Z axes.

A force effectiveness ratio (FER) was defined as the ratio of the force in the applied direction to the square root of the sum of the squares of the peak forces in the X, Y and Z directions:

$$FER = \frac{F_{applied}}{\sqrt{F^2_{x\ peak} + F^2_{y\ peak} + F^2_{z\ peak}}}$$

This parameter ranges from zero to one, and is an indication of how much of the subjects' total effort actually went into performing the desired task. A value of 1.0 meant that all of the force was applied in the intended direction; likewise, a value close to 0.0 meant that no force was applied in the intended direction. Note that the peak of each component of force was used to calculate the FER and that these individual peaks did not necessarily occur at the exact same time. Values for FER for the test conditions are listed in table 10. The data are also presented graphically in figure 16.

Table 10. Force Effectiveness Ratios for Each of the Directions of Effort

Direction of Applied Force	Tool Orientations	MAX	AVG
DOWN	YZ and ZY	.919	.884
UP	YZ and ZY	.911	.894
LEFT	XZ and ZX	.811	.746
RIGHT	XZ and ZX	.903	.861
AWAY	XY and YX	.703	.649
TOWARDS	XY and YX	.847	.801

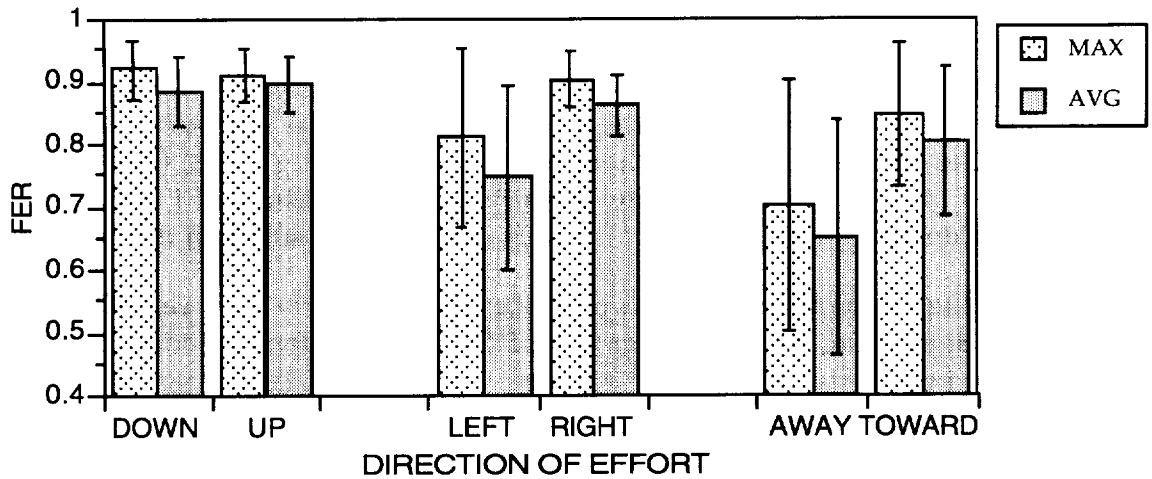

Figure 16. Bar chart of FER for each of the test conditions.

Statistical analysis showed that an effort in the "away" direction resulted in a lower FER than "towards", "right", "down", and "up" with both the MAX and AVG variables. In addition, with the AVG values, there was a difference between "up" and "left" efforts.

In this study, forces were reported. However, with most tool tasks, the goal is actually to generate a torque. To calculate the torque that would be produced, one can multiply the force in the applied direction by the moment arm of the tool. For example, with a moment arm of 17.8 cm (7 in.), the force data from table 9 was converted to torques and is presented in the table below. Values are in Newton-meters (foot-pounds in parenthesis).

Table 11. Torques in Direction of Effort With a Moment Arm of 7 Inches

Direction of Applied Force	Tool Orientations	MAX	AVG
DOWN	YZ and ZY	95.7 (70.6)	86.0 (63.5)
UP	YZ and ZY	128.5 (94.8)	119.4 (88.1)
LEFT	XZ and ZX	75.3 (55.6)	68.4 (50.5)
RIGHT	XZ and ZX	89.0 (65.7)	81.6 (60.2)
AWAY	XY and YX	73.6 (54.3)	64.1 (47.3)
TOWARDS	XY and YX	88.2 (65.1)	73.9 (54.6)

Torques with other moment arms can be calculated similarly.

CONCLUSIONS

This study was a generic examination of the loads produced by individuals performing maximal efforts with a torquing tool. Specifically, the purposes were to: (1) determine operator strength when performing torquing tasks; (2) quantify the loads placed on foot restraints while performing these tasks; and (3) examine effects of orientation and direction of rotation of tool on strength effectiveness.

It was seen that these subjects could produce approximately between 400 and 725 N of force, depending on the orientation of the tool and the direction of effort (table 9, columns 3 and 4). The most force could be produced when pushing the tool in an upwards direction.

The FER defined here was used as an indication of how much of the subjects' total effort actually went into performing the desired task. Values of the FER taken from the AVG data ranged from 0.65 to 0.89; for the MAX data the range was 0.70 to 0.92. The greatest FER occurred with UP and DOWN efforts. The lowest FER occurred with AWAY and LEFT efforts.

The foot restraint forces varied considerably, depending on the test conditions. Forces in the X direction, or head to foot, ranged from 41 N to 890 N. Forces in the Y direction, or right to left, were all less than 80 N. Forces in the Z direction, back to front, ranged from less than 5 N to nearly 190 N.

These results can be put to use in several ways. Designers can use the maximum loads in setting specifications for craft structures. Tools can be developed based on the known strength of the tool users. Finally, tasks can be developed so that the strength capabilities of the crewmembers are not exceeded.

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13. ABSTRACT *(Maximum 200 words)*

This study was a generic examination of the loads produced by individuals performing maximal efforts with a torquing tool in zero gravity, to determine operator strength when performing torquing tasks; quantify the loads placed on foot restraints while performing these tasks; and examine effects of orientation and direction of tool rotation on strength effectiveness.

The experiment was conducted aboard NASA's KC-135 reduced-gravity aircraft, using two force plates attached to a test stand, one with a foot restraint. Subjects used a wrench to apply maximum torques to various fittings, in different positions, in clockwise and counterclockwise directions.

It was seen that these subjects could produce approximately 400 to 750 N of force, depending on the orientation of the tool and the direction of effort. The most force could be produced when pushing the tool upwards. A force effectiveness ratio (FER) was defined as an indication of how much of the subjects' total effort actually went into performing the desired task. Values of FER ranged from 0.55 to 0.90, with the greatest FER occurring with UP and DOWN efforts, and the lowest with AWAY and LEFT efforts.

Designers can use these results to set specifications for craft structures; tools can be developed based on the known strength of the tool users; and tasks can be developed to not exceed the crewmembers' capabilities.

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